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Nuclear spins of the bismuth isotopes Bi^{199}, Bi^{200}, Bi^{201}, and Bi^{202}

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With 5 figures in the text

ABSTRACT

The atomic beam magnetic resonance method has been used for measurements of the ground-state spins of four short-lived bismuth isotopes with the following results: for Bi^{199} (25 min.) $I = 9/2$, for Bi^{200} (35 min.) $I = 7$, for Bi^{201} (1.85 hr) $I = 9/2$, and for Bi^{202} (1.6 hr) $I = 5$. All attempts to find the 1.0 hr isomeric state in Bi^{201} have been unsuccessful. The spin values obtained are discussed from the point of view of the nuclear shell model.

I. Introduction

With the measurements reported here, the program of determining the ground-state spins of neutron-deficient bismuth isotopes is complete. The spins of all isotopes with mass numbers from 199 through 206 have now been measured [1]. These cover a half-life range of 25 minutes to 14 days. Isotopes outside this region are either too long-lived ($\geqslant 8$ years) to give sources of enough strength, or too short-lived ($\leqslant 7$ minutes) to be handled with the present technique.

The experimental results are discussed in connection with simple considerations based on the nuclear shell model. It is found that the observed spin values are consistent with this model, although some irregularities in the coupling between the odd particles and in the filling order of the neutron levels must be assumed in order to explain the spins of Bi^{202} and Bi^{200}. There now seem to be enough experimental data in this region to warrant a more detailed theoretical investigation, which would give increased information about the neutron level systematics.

II. Experimental

The apparatus used in these experiments is the six-pole focusing atomic beam apparatus, which has been described in an earlier article [2]. The experimental procedure has also been reported previously [1, 3].

For the study of isotopes with half-lives of the order of half an hour, the apparatus has been modified and has been supplied with an arrangement for rapid exchange of the oven. Figure 1 shows the oven arrangement in detail. The oven is mounted on

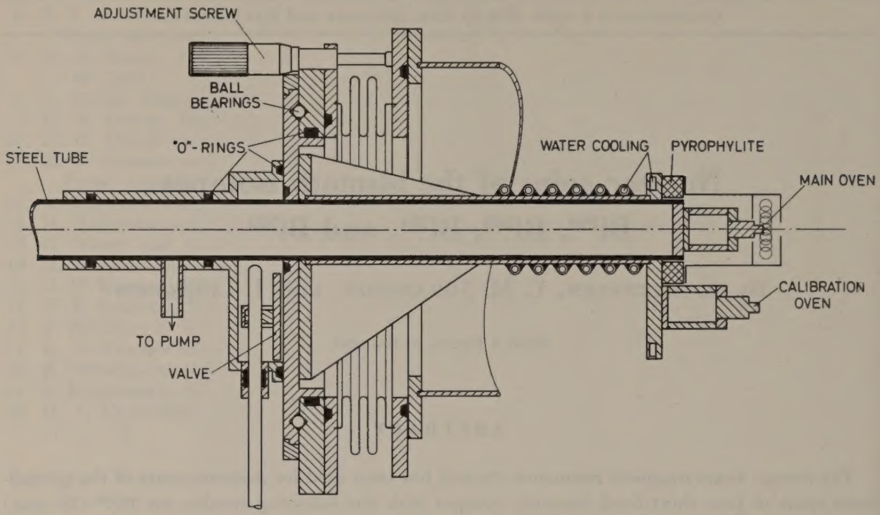

Fig. 1. The new oven arrangement, which allows a rapid exchange of the main oven through a vacuum lock. The positions of the two ovens are exchanged by rotating the oven holder around its horizontal axis.

a steel tube, which is pushed into a water-cooled brass tube. The radiation shields and the heating equipment as well as the calibration oven are mounted on a copper plate at the end of the brass tube. The main oven can be locked into the oven chamber in a few minutes without disturbing the high vacuum, so that the potassium beam can be used continuously for calibration of the C-field. The heating of the main oven is, as before, accomplished by electron bombardment.

The isotopes were produced in the synchro-cyclotron at the Gustaf Werner Institute at Uppsala by bombardment of lead with protons of various energies between 60 and 155 MeV. The chemical separation was made by internal electrolysis on nickel wires, as in the previous work [3]. This procedure was very rapid; in about ten minutes most of the bismuth activity was deposited on the wires. Totally, about 30–40 minutes were required to obtain a steady beam after the end of the irradiation. This means that isotopes with half-lives down to 15 minutes could be studied with this technique. In experiments with the isotopes Bi^{201} and Bi^{202}, the chemical separation was made 1–2 hours after the end of bombardment, in order to allow the more short-lived activities to decay. This was necessary since Bi^{199} has long-lived daughters.

The detection was performed in our usual manner [3]; the atoms were collected on carbon-coated metal foils, and the activity was measured by a conventional scintillation counter, which detects the X-rays following electron-capture decay.

Since the samples contained a great many isotopes, identification was important. This was accomplished by half-life determinations and by the fact that odd-mass isotopes have half-integral spins while even-mass isotopes have integral spins. For detection we have two counters, in order that one can be used for half-life determinations, while the other is used for the continuous measurements. When good

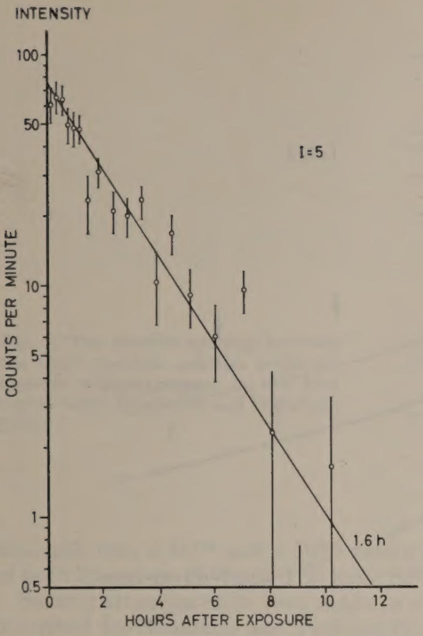

Fig. 2. Decay of the spin 5 signal.

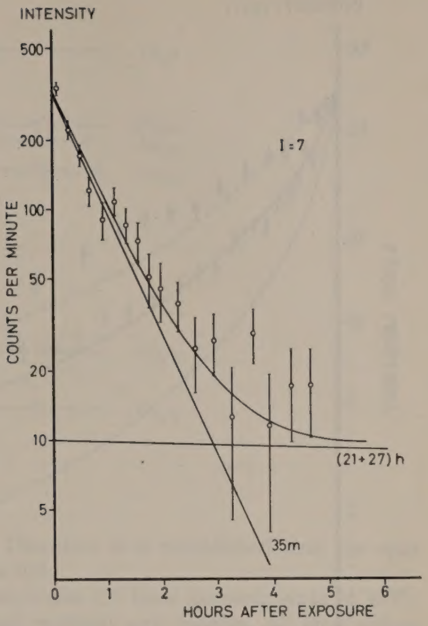

Fig. 3. Decay of the spin 7 signal.

statistics were needed, only a few exposures were made, which were then followed on both counters. Identification is fairly easy in the case of bismuth, since neighbouring odd-mass and even-mass isotopes, respectively, differ by at least a factor of three in half-life. For the odd-mass isotopes it is, however, somewhat complicated, because these isotopes have the same spin.

With the flop-in technique [2, 3] used here, two low-frequency transitions can be observed, corresponding to $F = I + J$ and $F = I + J - 1$. For all isotopes investigated, both lines were observed in at least three different magnetic fields in the range 1–5 gauss.

III. Results

Figure 2 shows the decay of the spin 5 signal. The line in the figure corresponds to the half-life of 1.6 hours, given by Karraker and Templeton [4] for Bi^{202}, and is in good agreement with the observed decay. Since only electron-capture decay is observed at the detection, the 3.7 hour isomeric transition in Pb^{202} cannot be seen. Therefore, the decay of the signal is simple. In figure 3 the decay of the spin 7 signal is given. This is found to agree very well with the Bi^{200} half-life of 35 minutes, reported by Neumann and Perlman [5]. The daughter activities in lead and thallium have been considered in constructing the decay line. No other bismuth activities from even-mass isotopes are known with half-lives of the same order. Therefore, the spin value 5 can be assigned to Bi^{202} and the spin value 7 to Bi^{200}.

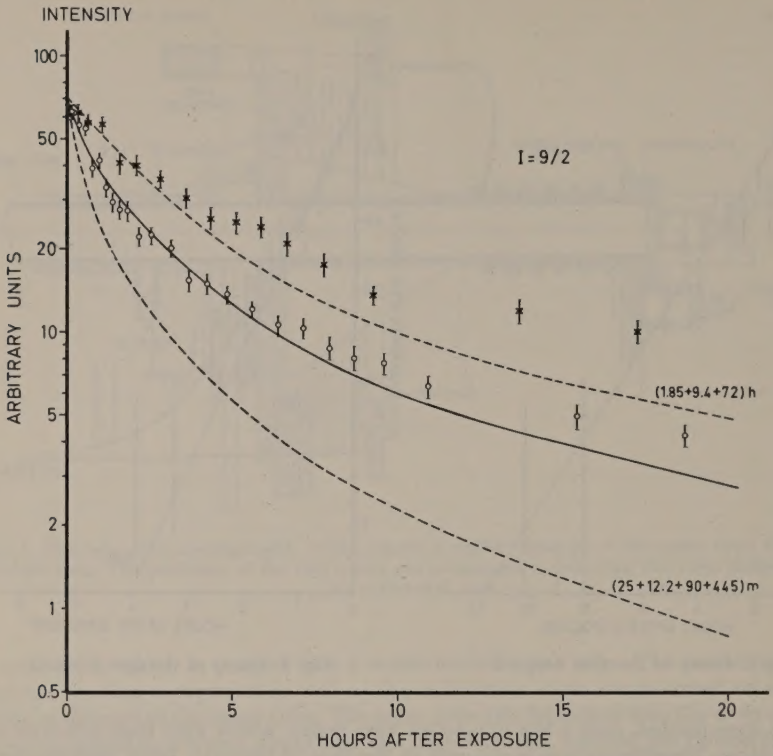

Fig. 4. Decays of two spin 9/2 signals, obtained 35 minutes (circular points) and 3 hours (crosses) after the end of the irradiation, respectively. The dashed curves are the theoretical decay curves of the Bi^{199} and the Bi^{201} activities, and the full curve is a composition of 50 per cent of each activity.

The decay of the spin 9/2 signal is very complex, since several isotopes have this spin value. Figure 4 shows the decay of two exposures made at different intervals after the bombardment. The bombarding energy was about 155 MeV (mean value), the maximum available in the cyclotron. The first signal was obtained about 35 minutes and the second about 3 hours after the end of the irradiation. Both decays start from the same point in the diagram, and the theoretical decay curves of the Bi^{199} and Bi^{201} activities have also been drawn from that point (dashed). These curves are based on half-life determinations by Neumann and Perlman [5] and Stockendal *et al.* [6]. At the beginning, the decay of the second signal is in agreement with that of Bi^{201}, while the first signal has a decay definitely intermediate between the two theoretical ones. The latter decay can be analyzed into about 50 per cent Bi^{199} and 50 per cent Bi^{201} activity (full curve). At the right part of the diagram the experimental points lie somewhat above the theoretical curves, which indicates that a small amount of Bi^{203} activity is present in the signal. The observed decays cannot be

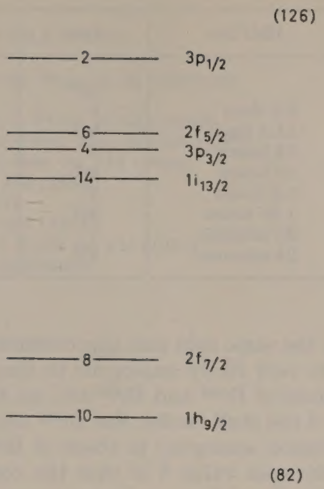

Fig. 5. The relative spacings between the single-particle neutron levels for neutron-deficient nuclei in the lead region (after Blomqvist and Wahlborn [10]).

analyzed into a Bi^{199} and a Bi^{203} activity. Therefore it is established that the spin of both 25 minute Bi^{199} and 1.85 hour Bi^{201} is 9/2.

Several attempts have been made to observe the 1.0 hour isomeric state in Bi^{201}, described by Neumann and Perlman [5], but without any success. All spin values between 1/2 and 21/2 have been investigated at several different magnetic fields, but no signal has been found. If the number of atoms in the isomeric state had been of the same order as that in the ground state, a definite signal should have been observed, provided that the magnetic moment is not very small ($\leqslant 0.1$ n.m.). The isomeric state is reported to decay mainly by electron capture and should thus be observable with our detecting device. If, however, the decay is an isomeric transition, the signal would appear first some time after the exposure because of the decay of the ground state. Therefore, to exclude this eventuality, the activity of the collectors was measured several times at intervals of about one hour.

IV. Discussion

The ground-state spins of eight neutron-deficient bismuth isotopes have now been measured with the atomic beam technique [1]. These isotopes together with Bi^{209} are tabulated below, and the most probable nuclear configurations are given. The calculated neutron levels in this region are shown in figure 5.

All the odd-even isotopes have the spin 9/2. This is to be expected, since, according to the nuclear shell model, the odd proton should be in the level $h_{9/2}$ and an even number of neutrons always couple to a resultant spin zero.

Bi^{206} has been investigated theoretically by Wahlborn [7], who obtained the ground-state configuration given in the table and the spin value 6. The configuration assignment is also supported by the value of the magnetic moment, which is in good agreement with the theoretical value calculated from this configuration [3].

Isotope	Half-life	Spin	Configuration
Bi^{209}		9/2	$\pi h_{9/2}$
Bi^{206}	6.3 days	6	$\pi h_{9/2} (\nu p_{1/2})^{-2} (\nu f_{5/2})^{-1}$
Bi^{205}	14.5 days	9/2	$\pi h_{9/2} (\nu p_{1/2})^{-2} (\nu f_{5/2})^{-2}$
Bi^{204}	13 hours	6	$\pi h_{9/2} (\nu p_{1/2})^{-2} (\nu f_{5/2})^{-3}$
Bi^{203}	12 hours	9/2	$\pi h_{9/2} (\nu p_{1/2})^{-2} (\nu f_{5/2})^{-4}$
Bi^{202}	1.6 hours	5	$\pi h_{9/2} (\nu p_{1/2})^{-2} (\nu f_{5/2})^{-5}$
Bi^{201}	1.85 hours	9/2	$\pi h_{9/2} (\nu p_{1/2})^{-2} (\nu f_{5/2})^{-6}$
Bi^{200}	35 minutes	7	$\pi h_{9/2} (\nu p_{1/2})^{-2} (\nu f_{5/2})^{-5} (\nu p_{3/2})^{-2}$ (?)
Bi^{199}	25 minutes	9/2	$\pi h_{9/2} (\nu p_{1/2})^{-2} (\nu f_{5/2})^{-6} (\nu p_{3/2})^{-2}$ (?)

Since Bi^{204} has the same spin and approximately the same magnetic moment [3], the configuration is very likely analogous to that of Bi^{206}.

The spin values of Bi^{202} and Bi^{200} are, on the contrary, more surprising from the point of view of the shell model. For Bi^{202} one would have expected the spin value 6 and a configuration analogous to those of Bi^{204} and Bi^{206}. The most reasonable explanation of the spin value 5 is that the configuration is the same, but that the coupling between the odd proton and neutron is different from that in Bi^{204} and Bi^{206}. This state is analogous to the lowest state with the spin value 5 in Bi^{206} [7]. It is difficult to explain this spin value with another configuration; e.g., with the odd neutron in the $p_{3/2}$ level, the spin should be 3 according to Nordheim's strong rule [8].

The spin value 7 of Bi^{200} is also difficult to explain on the basis of the extreme single-particle model. With a two particle configuration the neutron spin must be $\geqslant 5/2$. Therefore, if the $f_{5/2}$ level is empty, the odd hole must be in one of the levels $i_{13/2}$, $h_{9/2}$, or $f_{7/2}$. A more probable explanation is that there is an irregularity in the filling order of the neutrons, so that there is a single neutron in the $f_{5/2}$ level and two holes in another level, e.g., the $p_{3/2}$ level. The spin value 7 would then be in agreement with Nordheim's weak rule [8]. The configuration assignments of Bi^{202} and Bi^{200} are also in agreement with spectroscopical measurements, according to which the ground-state spins of Pb^{201} and Pb^{199} are supposed to be 5/2 [9]. One must bear in mind, however, that the extreme single-particle model cannot be expected to be a very good approximation so far from closed shells, (Bi^{200} has 9 neutron holes). The total spin might be formed by several particles in the unfilled single-particle levels, not only the odd ones.

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REFERENCES

1. C. M. Johansson and I. Lindgren, Nucl. Phys. *9*, 44 (1958/59).
2. I. Lindgren, Nucl. Instr. *3*, 1 (1958).
3. I. Lindgren and C. M. Johansson, Ark. f. Fysik *15*, 445 (1959).
4. D. G. Karraker and D. H. Templeton, Phys. Rev. *81*, 510 (1951).
5. H. M. Neumann and I. Perlman, Phys. Rev. *78*, 191 (1950).
6. R. Stockendal *et al.*, Ark. f. Fysik *11*, 165 (1956).
7. S. Wahlborn, Nucl. Phys. *3*, 644 (1957).
8. L. W. Nordheim, Rev. Mod. Phys. *23*, 322 (1951).
9. I. Bergström and G. Andersson, Ark. f. Fysik *12*, 415 (1957).
10. J. Blomqvist and S. Wahlborn, to be published.

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